Analysis of coupling losses in multifilamentary untwisted BSCCO/Ag tapes through a.c. susceptibility measurements

D. Zola, F. Gömöry, M. Polichetti, F. Strycek, J. Souc, P. Kovák and S. Pace

***Abstract*— Losses as function of the a.c. magnetic field amplitude (B_0) were measured at 77 K in untwisted BSCCO(2223)/Ag tapes, at different frequencies, by measuring the imaginary part of the a.c. susceptibility. In particular, loss measurements were performed in the portions of the same tape, obtained by cutting it in pieces with different length, starting from around 12 cm down to 1 cm. The results show that the measured losses depend on the sample length but this observed behaviour is not always due to the coupling mechanism among the filaments. In this work we discuss the observed experimental behaviour of different typology of tapes by analysing data comparing them with analytical models in order to fully characterize the tapes with regard to the coupling mechanism.**

***Index Terms*— a.c. losses, BSCCO tapes, a.c. susceptivity**

I. Introduction

IN A.C. electrical devices make by superconductors cables is necessary to reduce the a.c. losses arising by the hysteretic, coupling and eddy mechanisms [1]–[3]. Tapes or wires usually contains many superconducting filaments because in this way the hysteretic losses are reduced. These filaments in BSCCO tapes, are embedded in metallic matrix, usually in silver or silver alloy for improving the thermal stability and the mechanical properties of tapes. On the other hand, to cut down the coupling losses, it is essential to reduce the area of induced flux e.g. by twisting the filaments or increasing the matrix resistivity or manufacturing artificial resistive barriers around the filaments. Nevertheless, the efforts turned towards a reducing of losses in a tape can be compromised by the intergrowths and bridging which can decrease the effective resistivity of the matrix or electrically connect the superconducting filaments [4], [5].

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The coupling loss per unit volume and per cycle (Q_c) if the a.c. magnetic field amplitude $B_0 \ll B_p$,which is the full penetration field of the tape, is given by [6], [7]:

$$Q_c = \frac{B_0^2}{2\mu_0}\left[2\pi\chi_0\left(\frac{\omega\tau}{1+\omega^2\tau^2}\right)\right] \tag{1}$$

where τ is so called time constant, χ_0 is a constant depending on geometry related to demagnetization factor and ω is the angular frequency. The Eq. 1 shows as the coupling loss depends on frequency and on B_0 square whereas the hysteretic loss depends on B_0^3 [1], [8] and it has a very slight dependence on frequency. The different behaviour on frequency and on B_0 can be employed to discriminate the different loss mechanism. The Equation 1 has a maximum for $\omega\tau = 1$ which can be experimentally so estimated by finding the frequency (ν_m) where the maximum occurs in loss measurements performed at low B_0 [9]–[11].
At the same time, loss are linked to the imaginary part of the first harmonic of the a.c. susceptibility χ'' [3], [7], [12] according to:

$$Q = \pi\chi''\chi_0 B_0^2/\mu_0 \tag{2}$$

Both Q and τ can be also evaluated by a.c. susceptibility measurements also because χ_0 can be experimentally measured [13] Moreover, in untwisted BSCCO tapes, τ is given by:

$$\tau = \frac{\ell^2\mu_0}{\pi^2\chi_0\rho_m} \tag{3}$$

and therefore the time constant depends on the square of the length (ℓ) , on the effective resistivity (ρ_m)and on the tape geometry factor (χ_0) [12], [13]) The effective resistivity generally differs from the bare matrix resistivity, because it depends on the tape geometry and on the particular arrangement of the superconducting filaments [14] and by evaluating τ the effective resistivity can be, in this way, estimated [7].

In this work, the coupling losses have been analysed in commercial multifilamentary untwisted tape and compared with tapes with a geometry resembling just two filaments separated by a metallic matrix. In this last case, each ”filament” consists in dense stack of extremely flat filaments. We have measured by a.c. susceptibility technique, the losses as function of frequency when the external magnetic field is perpendicular to the broad face of the sample. In order to study the effect of the sample length on the losses, the measurements were repeated for the same tape, cut several times in shorter and shorter pieces. Since we expect that the hysteresis loss has

not to vary as the length is changed (whereas the coupling loss depends strongly on the sample length), we want to characterize the quality of the tapes from bridging aspects. Finally, the measurement have been performed in a frequency range that the eddy loss have been estimated negligible.

II. Experimental

The a.c. losses were measured by using an a.c. susceptometer with a system of coils suitable for measurements on sample with length up to 12 cm An electromagnet produces an a.c. magnetic field with B_0 up to 50 mT, with a field homogeneity within 1% on a 8 cm length and 2% on 12 cm. The a.c. field induces a voltage in two racetrack-shaped coils: the pick-up coil, which is very close to the sample surface, while the null coil is 1 cm apart. Since the pick-up coil and the null coil are not perfectly identical, a variable compensation system is also used. The a.c. magnet and both the coils are placed in a reinforced plastic cryostat, so no eddy currents are induced in the cryostat walls. The system is cooled by liquid nitrogen and all the measurements have been performed at 77 K. Measurements have been performed in the frequency range from 1 Hz to 1000 Hz in the field amplitude ranging from 0.05 mT to 45 mT.

A.C. susceptibility measurements have been performed on two bi-columnar tapes of around 61 mm. The first (named in the following "Ag tape") was prepared with 16 filaments in pure silver matrix with a stack of 8 filaments for each column separated by about 0.3 mm of pure silver. The external sheath is also made with the same material.The geometry of the second tape (Ag/Mg tape) is similar to that of Ag tape, but the number of filaments is 15 and therefore there are 8 filaments in one column and 7 in the other. The metallic sheet between filaments is a Ag/Mg(0.4%) alloy and the matrix which embeds the whole filamentary zone is a Ag/Mg(0.4%)/Ni(0.22%) alloy. Moreover, other a.c. susceptibility measurements have been performed on commercial tapes, manufactured by Australian Superconductor (AUS) and by Nordic Superconductor Technologies (NST), whose we have few technical data. The NST samples have 65 filaments embedded in unknown matrix (probably Ag-Mg alloy) and the cross section dimensions are 3.2 mm $\times$ 0.30 mm. We do not know the fill factor of the tapes neither the critical current. The Australian tapes have 37 filaments and a critical current of 36-38 A. The cross section is 2.96 mm $\times$ 0.33 mm, the fill factor is unknown and the metallic matrix is probably in Ag/Mg alloy.

In all tape the geometrical factor χ_0 has been measured according the technique reported in Ref. [13]. I measured value of χ_0 are respectively 8.9 in Ag tape, 8.8 in Ag/Mg tape whereas it is 3.6 in NST tape and 5.1 in AUS tape.

III. Frequency and B_0 dependence of losses in bicolumnar tape

Losses have been measured as function of B_0, in several pieces with different lengths, cut from our original Ag and Ag/Mg tapes. In the upper graph of the Fig. 1, the $\chi''(B_0)$ is shown as measured on a Ag tape of 61.7 mm at different frequencies. For $B_0 < B_{0,max}$(which is the field value where

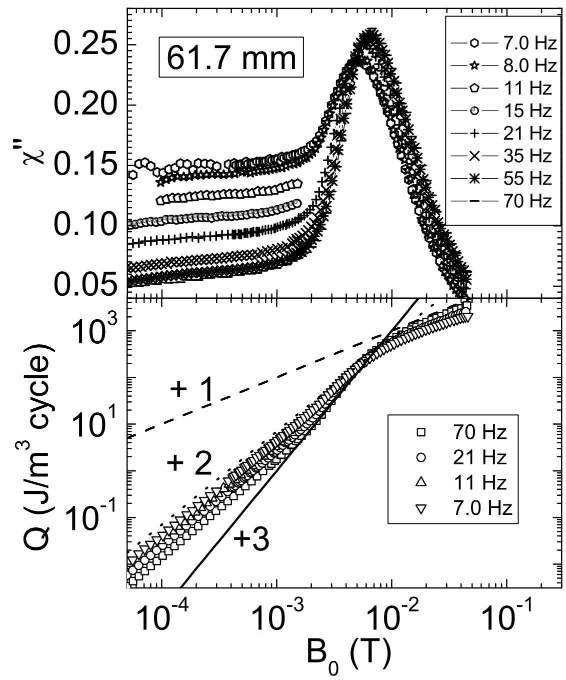

Fig. 1. B_0 dependence of χ''(upper graph)and of the loss (lower graph)in log-log scale as measured in Ag tape of 61.7 mm. The lines shown the expected dependence, for $B_0 < B_{0,max}$, of the hysteretic loss (continuous line) and of the coupling loss (dotted line). The dashed lines is the expected behaviour of both losses when $B_0 > B_{0,max}$

χ'' has a maximum and it is around two time the full penetration field (B_p)of tape), the susceptibility has a large frequency dependence. At low field amplitudes, χ'' is nearly constant and the slight dependence on B_0 is probably due to the hysteretic contribution of the superconducting columns. However, as shown in the lower graph of the same figure, the loss densities have a quadratic slope as expected if the coupling mechanism leads through losses. At high field, the imaginary part and the Q take a behaviour similar to the hysteretic one due to a full coupling of the two superconducting columns [6], [10].

Losses have been investigated as function of the frequency at a fixed field amplitude much lower than $B_{0,max}$. As reported in figure 2, the losses exhibit a maximum that shifts towards higher frequencies as the samples length decreases. The experimental data have been fitted by

$$Q_{fit}(\omega) = \alpha \frac{\omega\tau}{1 + \omega^2\tau^2} + \beta \tag{4}$$

where β is added for considering the hysteretic contribution of the two columns. The experimental data are well fitted by the (4) with apart the experimental data measured in the sample 15.4 mm long of the Ag tape. The τ values, obtained from the fits, are reported in table Iand by using the (3), the effective resistivity of the metallic matrix has been determined. Since the resistivity of the silver is 4 times smaller than that of the Ag/Mg alloy and since the structure of the two tapes is similar, it is surprising to see that the experimental data reported in table I demonstrate that Ag tape has a lower effective resistivity than the Ag/Mg tape. These results can

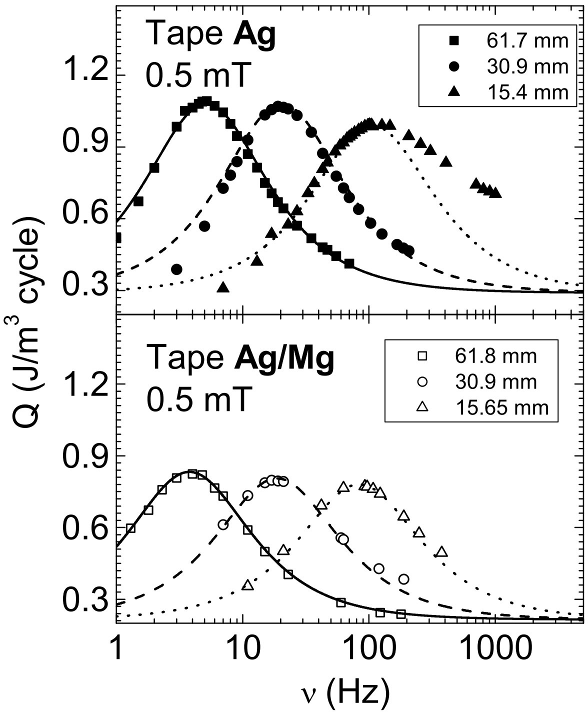

Fig. 2. Frequency dependence of the losses of Ag tape (upper graph) and Ag/Mg tape (lower graph) as measured in samples of different lengths. The lines are the fit obtained by using the (4)

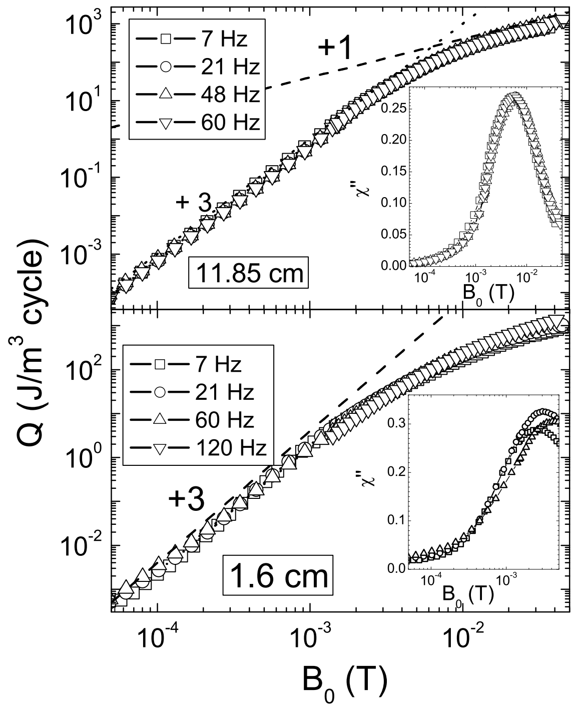

Fig. 3. Losses as function of the magnetic field amplitudes (in log-log scale) estimated on a NST multifilamentary tape cut in pieces of different length, measured at different frequencies. In the inset, the $\chi''(B_0)$ curves are shown, from which the losses have been estimated.

TABLE I

VALUES OF THE QUANTITIES τ, AND ρ_{eff} AS DETERMINED FROM THE EXPERIMENTAL DATA FOR ALL THE CONSIDERED SAMPLES.

	ℓ (mm)	τ (ms)	ρ_{eff} ($\mu\Omega$ cm)
Ag tape			
	61.7	31	0.176
	30.9	7.8	0.175
	15.5	1.75	0.192
	6.5	0.32	0.172
Ag/Mg tape			
	61.8	42	0.132
	30.9	8.9	0.155
	15.6	1.9	0.182

be understand knowing that high density of inter-growths is quite common tapes with matrix in Ag/Mg alloy [5].

IV. Coupling losses in commercial tapes

In the previous section, we have shown as by mean a.c. susceptibility measurements, the bi-columnar tapes have been fully characterized, in particular evaluating the effective resistivity of the metallic matrix. On the same time, we have also verified that the classical model on coupling losses works very well also if this is used to analyse the coupling mechanism in BSCCO/Ag tapes. We want to extend this analysis to commercial tapes which are the serious candidate for applications.

In the figures 3 and 4 the losses measured on NST tapes and AUS tapes of different length are shown. Looking at the Fig. 3, we can observe in upper and lower graph that the losses have a cubic dependence at low field whereas the slope becomes +1 at high field. This behaviour behaviour is observed on the sample 11.85 cm long as in the sample of 1.6 cm and equivalent results have been found at intermediate lengths. At the same time, the imaginary part of the a.c. susceptibility has not any frequency dependence. The analysis performed on these tapes lead us to conclude that in NST tape the coupling are completely suppressed for effect of a very strong bridging among the filaments that lead to a behaviour very similar to a monofilamentary tape with hysteretic loss only.

In AUS tapes we can observe a more interesting behaviour. The losses have been measured on samples with length starting from 11.1 cm down to 1.3. At low field, the slope of the losses in log-log scale is close to 2.5 as on sample 11.1 cm long as on a piece of only 1.3 cm. The value of the slope confirms that the coupling mechanism competes with hysteretic one for every length. In the two inset of the figure, the imaginary part of the AUS tapes as measured in a piece of 11.1 cm and 1.3 cm show a some frequency dependence. Similar measurements,no shown, have been performed on a sample 5.5 cm long and they have an equivalent behaviour. In particular in the two inset of Fig. 4 we can observe the low field region of the a.c susceptibility measured at different frequencies. In the sample 11.1 cm long, the χ'' decreases as the frequency increases and this could meaning that the maximum of the coupling losses is at lower frequency. As shown in previous section, cutting the sample this maximum shift at higher frequency. In the 5.5 cm sample the χ'' seems to have a maximum between 7 Hz and 21 Hz whereas in the sample 1.3 cm long this maximum

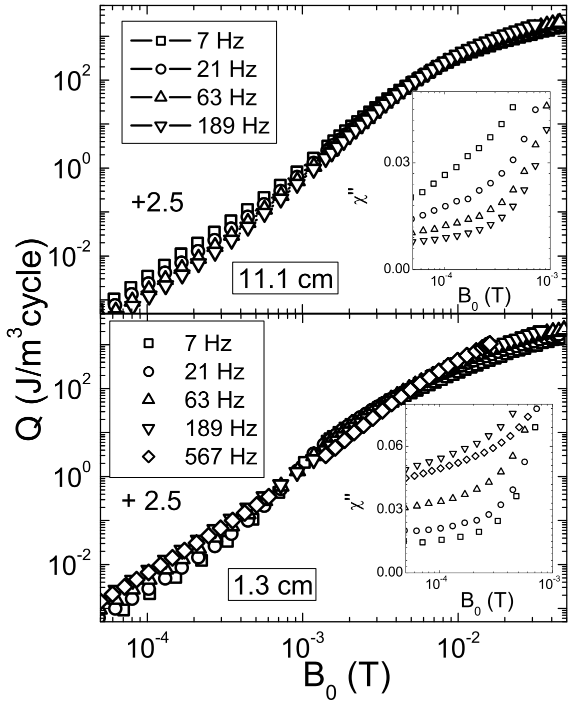

Fig. 4. Losses as function of the magnetic field amplitudes (in log-log scale) estimated on a AUS multifilamentary tape cut in pieces of different length, measured at different frequencies. In the inset, the $\chi''(B_0)$ curves are shown, from which the losses have been estimated.

seems to be at frequency around 189 Hz with a saturation measured up to 567 Hz. The frequency trend of AUS tape does not resemble exactly the quasi ideal behaviour of the bi-columnar tapes. On the other hand, we know that in pure metal the value of χ'' when $\omega\tau = 1$ is 0.38 whereas it is, in general, smaller in a filamentary superconductor surrounded by a metal. For example in the bicolumnar tapes, where the coupling mechanism is dominant, at 0.1 mT the maximum value of the susceptibility is around 0.15 which is 3 times larger than the value measured on AUS tapes at the same field. All these considerations lead us to conclude that in AUS tapes a part of tape is strong bridged probably in the more densely packed region but an other part the bridge is not so strong and a coupling mechanism can arise. Nevertheless the large hysteretic terms is comparable with the coupling loss and we cannot fully characterize the samples. However, through this investigation we have acquired important informations on the a.c. behaviour of tapes potentially employed in the realization of applications investigating deeply the filamentary nature of the BSCCO tapes.

V. Conclusions

In this work we have studied the a.c. coupling losses on two different sets of tapes, bicolumnar BSCCO tapes and commercial tapes. A.C. susceptibility and losses, measured as function of the magnetic field amplitude and frequency, show that the coupling losses dominate in bi-columnar tapes over the hysteretic losses of the single filaments. The experimental effective resistivity in Ag tape has a higher value in comparison with Ag/Mg tape which has a ρ_{eff} lower than expected. This results are explained with the presence of intergrowths in Ag/Mg tapes and this result suggests that in this kind of tapes, the enhancement of the effective matrix resistivity does not reduce automatically the coupling losses. In NST tapes we have found a very strong bridging which lead to suppress completely the coupling mechanism and the tape works like a monofilamentary tape. Finally in AUS tapes the coupling mechanisms competes with a large hysteretic component, probably due to a strong bridging in a significatively part of the tape. Our work show as through a.c. susceptibility it is possible to investigate the quality of BSCCO/Ag multifilamentary tapes.

References

[1] W. Carr, *AC Loss and macroscopic theory of superconductors*. New York: Gordon and Breach, 1983.

[2] S. Takács, "Ac losses in superconducting cables and their expected values in magnetic systems," *Superconductor Science and Technology*, vol. 10, p. 733, 1997.

[3] J. R. Clem, "Ac losses in type-ii superconductors," in *Magnetic Susceptibilites of Superconductors and Other System*, E. by R. A. Hein T. L. Francavilla and D. H. Liebenberg, Eds. Plenum Press, New York and London, 1991.

[4] M. Dhallé, R. Passerini, E. Giannini, G. Witz, J.-Y. Genoud, Y. Huang, X.-D. Su, and R. Flüukiger, "The formation mechanism of bi, pb(2223) outgrwths in multi-filamentary tapes," *IEEE Trans. Appl. Supercond*, vol. 11, p. 3557, 2001.

[5] Y. Bugoslavsky, Y. G. K. Perkins, P. Busceni, and A. Caplin, "Inhomogeneity of current distribution in multifilamentary biscco-2223 tapes," *Superconducting Science Technology*, vol. 14, p. 245, 2001.

[6] A. M. Campbell, "A general treatment of losses in multifilamentary superconductors," *Cryogenics*, vol. 22, p. 3, 1982.

[7] D. Zola, F. Gömöry, M. Polichetti, F. Strýček, E. Seiler, I.Hušek, P. Kováč, and S. Pace, "A study of coupling loss on bi-columnar bscco/ag tapes through ac susceptibility measuremets," *Superconducting Science and Technology*, vol. 17, p. 501, 2004.

[8] C. Bean, "Magnetization of hard superconductors," *Review of Modern Physics*, vol. 36, p. 31, 1964.

[9] K. Kwasnitza, "ac losses of multifilament superconductors reduced below the level of filament hysteresis losses due to field screening by filament coupling currents," *Cryogenics*, vol. 17, p. 613, 1977.

[10] ——, "scaling law for the ac losses of multifilament superconductors," *Cryogenics*, vol. 17, p. 616, 1977.

[11] K. Kwasnitza and S. Clerc, "Ac losses of superconducting high-t$_c$ multifilament bi-2223/ag sheated tapes in perpendicular magnetic fields," *Physica C*, vol. 233, p. 423, 1994.

[12] P. Fabbricatore, S. Farinon, S. Innocenti, and F. Gömöry, "Magnetic flux shielding in superconducting strip arrays," *Physical Review B*, vol. 61, p. 6413, 2000.

[13] P. Fabbricatore, S. Farinon, F. Gömöry, and S. Innocenti, "Ac losses in multifilamentary high-tc tapes due to a perpendicular ac magnetic field," *Superconducting Science and Technology*, vol. 13, p. 1327, 2000.

[14] M. Oomen, J. Rieger, M. Leghissa, and B. ten Haken, "Effective transverse resistivity in superconducting tapes with various filament shapes and structures," *Superconducting Science and Technology*, vol. 13, p. 1101, 2000.